

# First Order Calculation of the Inclusive Cross Section $pp \rightarrow ZZ$ by Graviton Exchange in Large Extra Dimensions

Martin Kober<sup>1,\*</sup>, Benjamin Koch<sup>1,2</sup>, and Marcus Bleicher<sup>1</sup>

<sup>1</sup> *Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität,  
Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany*

<sup>2</sup> *Frankfurt Institute for Advanced Studies (FIAS),  
Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany*

(Dated: February 1, 2008)

We calculate the inclusive cross section of double Z-boson production within large extra dimensions at the Large Hadron Collider (LHC). Using perturbatively quantized gravity in the ADD model we perform a first order calculation of the graviton mediated contribution to the  $pp \rightarrow ZZ + x$  cross section. At low energies (e.g. Tevatron) this additional contribution is very small, making it virtually unobservable, for a fundamental mass scale above 2500 GeV. At LHC energies however, the calculation indicates that the ZZ-production rate within the ADD model should differ significantly from the Standard Model if the new fundamental mass scale would be below 15000 GeV. A comparison with the observed production rate at the LHC might therefore provide direct hints on the number and structure of the extra dimensions.

## I. INTRODUCTION

The possible existence of additional spatial dimensions has been a fascinating topic for theoretical physicists since the early ideas of Kaluza and Klein [1, 2]. The explanation why the additional dimensions have not been discovered so far can be given by the assumption that the additional dimensions are compactified to a very small radius. Usually the length scale of the compactified dimensions is assumed to be of the order of the Planck scale  $M_P \sim 10^{19}$  GeV and therefore far away from the scope of experimental physics.

However there is the possibility that the additional dimensions could be realized in a different way [3, 4, 5, 6, 7]. In the ADD model [8] the assumption is that the additional dimensions could be realized with a much larger compactification radius and much smaller fundamental scales, thus opening the possibility to observe deviations from the Standard Model (SM) at energies available at the LHC. According to the ADD model all matter fields of the SM live on the (3+1)-dimensional submanifold describing usual space-time and only gravity can propagate into the extra dimensions. This model yields an explanation why gravity appears to be so weak compared to the other interactions existing in nature (thus circumventing the hierarchy problem). The ADD model goes hand in hand with the definition of a higher dimensional Planck mass  $M_D$  related to the four dimensional Planck mass  $M_P$  by the following equation

$$M_P^2 = 8\pi M_D^{d+2} R^d, \quad (1)$$

where  $d$  is the number of extra spatial dimensions and  $R$  is their size. This effective reduction [44] of the Planck

scale leads to interesting effects for the production of gravitons. While in usual perturbatively quantized gravity the effects of incorporating virtual gravitons can be neglected because they are suppressed by factors of  $1/M_P$  the situation with the ADD model is different. By introducing additional dimensions according to the ADD model, the production and exchange of gravitons can lead to observable effects [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

The most prominent prediction of the ADD model is probably the possible production of microscopical black holes in upcoming collider experiments [19, 25, 26, 27, 28, 29]. As exciting the production (and subsequent evaporation) of a black hole in the laboratory might be, as a non-perturbative process in quantum gravity it is difficult to make quantitative predictions for the measurement of such events. The sum of these difficulties makes most predictions which are derived from black hole production model dependent. It is therefore desirable to have complementary observables which allow to test a specific model in a more quantitative way.

One possible approach that allows for a perturbative calculation is to consider the much larger number of possible couplings between the Kaluza-Klein towers in the perturbative gravitation sector of the ADD model and the SM. This results for instance in an enhanced gravitational radiation into the extra dimensions [30, 31, 32, 33, 34] becoming more and more important at higher energies. It also leads to new contributions to SM physics due to virtual graviton exchange [9, 11, 14]. Such contributions are mostly undetectable because of the much larger SM background. Ideally one is looking for SM processes that have a very clear experimental signal but a very low cross section. Further, those processes should also have some tree-level contributions in the ADD model.

In this paper we suggest to look for the production of Z-boson pairs, as it is done for a stabilized Randall-

---

\*Electronic address: kober@th.physik.uni-frankfurt.de

Sundrum scenario in [35]. For the case of the ADD model in [12] there is already considered production of a  $Z$ -pair by graviton exchange for the LEP and the Tevatron on the one hand and the decay mode  $Z \rightarrow f\bar{f} + \mathcal{G}$  on the other hand. According to these considerations there are obtained constraints for  $M_D$  below 1 TeV. However, we show that  $ZZ$ -production at the LHC can lead to constraints for  $M_D$  far above 1 TeV.

In the SM the process of  $ZZ$ -production is suppressed due to the two electroweak couplings and due to the large  $ZZ$ -production threshold. Another nice feature of this process at lowest order in the perturbative expansion is that the ADD contribution completely decouples from the SM cross section and can be treated separately.

In the following section we present the prerequisites for the effectively quantized gravity calculation in higher dimensions. After this we will consider  $ZZ$ -production in (anti-)proton-proton collisions by graviton exchange at tree-level. We will see that at least in case of a  $D$ -dimensional Planck mass  $M_D$  in the TeV region the extra dimensional contribution to the SM cross section leads to a substantial deviation from the well known  $ZZ$ -production rate of the SM.

## II. EFFECTIVE QUANTUM FIELD THEORY OF GRAVITY IN HIGHER DIMENSIONS

Let us shortly remind the reader on the effective field theory of gravity in extra dimensions given in [9, 11, 36]. Here, a small perturbation  $h_{MN}$  of the metric of flat Minkowski space-time  $\eta_{MN}$  is considered. The complete metric  $g_{MN}$  is then given by

$$g_{MN} = \eta_{MN} + 2M_D^{\frac{(D-2)}{2}} h_{MN} \quad . \quad (2)$$

In the present case of additional dimensions the indices  $M$  and  $N$  run from 1 to  $D = (3 + d) + 1$ . According to this a space-time point is described by a  $D$ -tuple  $(t, \mathbf{x}, y_4, \dots, y_d)$ . The Einstein-Hilbert action according to the Einstein equations in  $D$ -dimensions reads

$$S = \frac{1}{2} M^{D-2} \int d^D x \sqrt{-g} R \quad , \quad (3)$$

where  $g$  describes the determinant of the metric. Using the expansion (2) in (3) leads to the following Lagrangian

$$\begin{aligned} \mathcal{L}_h = & -\frac{1}{2} \partial_M \partial^M h + \frac{1}{2} \partial_R h_{MN} \partial^R h^{MN} \\ & + \partial_M h^{MN} \partial_N h - \partial_M h^{MN} \partial_R h_N^R \quad . \end{aligned} \quad (4)$$

The  $d$  additional dimensions are assumed to be compactified to a  $d$ -dimensional torus with radii  $R$  meaning that the coordinates belonging to the additional dimensions are periodic with respect to the transformation

$y_j \rightarrow y_j + 2\pi R, j = 4, \dots, d$ . Thus, the perturbation of the metric field can be expressed as

$$h_{MN}(z) = \sum_{j=1}^d \sum_{n_d=-\infty}^{\infty} \frac{h_{MN}(x)}{\sqrt{V_d}} e^{i \frac{n_j y_j}{R}} \quad . \quad (5)$$

This leads to an effective Lagrangian on the 3+1-dimensional submanifold of the following form

$$\begin{aligned} \mathcal{L}_h = & -\frac{1}{2} \partial_\mu \partial^\mu h + \frac{1}{2} \partial_\rho h_{\mu\nu} \partial^\rho h^{\mu\nu} + \partial_\mu h^{\mu\nu} \partial_\nu h \\ & - \partial_\mu h^{\mu\nu} \partial_\rho h_\nu^\rho - \frac{1}{2} m^2 (h^{\mu\nu} h_{\mu\nu} - h^2) \quad . \end{aligned} \quad (6)$$

The occurring mass of the graviton corresponds to the excitations of the gravitational field in the compactified dimensions and is related to them according to the equation

$$m_n^2 = \sum_{j=1}^d \left( \frac{n_j^2}{R^2} \right) \quad . \quad (7)$$

By following the path integral quantization procedure one is lead to the expression for the graviton propagator. The effective mass of the graviton breaks the usual gauge invariance of gravitation

$$x_\mu \rightarrow x_\mu + \epsilon_\mu \quad , \quad h_{\mu\nu} \rightarrow h_{\mu\nu} - (\partial_\mu \epsilon_\nu + \partial_\nu \epsilon_\mu) \quad , \quad (8)$$

and thus the Faddeev-Popov procedure can be omitted. The graviton propagator is then

$$\Delta_{\mu\nu\rho\sigma}(x, y) = \int \frac{d^4 k}{(2\pi)^4} \frac{P_{\mu\nu\rho\sigma}(k)}{k^2 - m_n^2} e^{-ik(x-y)} \quad , \quad (9)$$

with polarization-tensor

$$\begin{aligned} P_{\mu\nu\rho\sigma}(k) = & \frac{1}{2} (\eta_{\mu\rho} \eta_{\nu\sigma} + \eta_{\mu\sigma} \eta_{\nu\rho}) - \frac{1}{2} \eta_{\mu\nu} \eta_{\rho\sigma} \\ & - \frac{1}{2m^2} (\eta_{\mu\rho} k_\nu k_\sigma + \eta_{\mu\sigma} k_\nu k_\rho + \eta_{\nu\rho} k_\mu k_\sigma + \eta_{\nu\sigma} k_\mu k_\rho) \\ & + \frac{1}{6} (\eta_{\mu\nu} + \frac{2}{m^2} k_\mu k_\nu) (\eta_{\rho\sigma} + \frac{2}{m^2} k_\rho k_\sigma) \quad . \end{aligned} \quad (10)$$

By addition of the terms arising from the energy-momentum tensor of the matter and interaction fields [9] the vertices are obtained. In the limit of a weak gravitational field only the matter and interaction fields of the SM fields (assumed to live on the 3+1-dimensional submanifold) contribute to the energy momentum tensor. It is therefore given by

$$T_{AB}(z) = \eta_A^\mu \eta_B^\nu T_{\mu\nu}(x) \delta(y) \quad . \quad (11)$$

### III. S-MATRIX AND CROSS SECTION

In the perturbative approach we use the SM couplings  $\sqrt{\alpha_{ew,strong}}$  and the ratio  $m_X/M_D$  as smallness parameters, where  $m_X$  stands for the mass scale in the process (in our case essentially the Z-boson). First, the collision processes of the partons, the quarks and gluons within the proton, have to be regarded. We restrict our analysis to processes at tree-level.

The processes corresponding to the Feynman diagrams displayed in figures (1), (2) and (3) contribute to the cross section for the quark anti-quark process of the SM. In leading order, there is no contribution from the gluons in the SM. Although SM calculations to higher orders in perturbation theory are feasible [37], they are neglected here, because one would also have to do higher orders in the ADD extension for consistency. However, as the ADD extension of the SM is non-renormalizable, those higher order calculations would not provide new insight or better accuracy. We will therefore limit ourselves to tree-level calculations, which are standard and will not be shown in detail here. As the parton distribution functions are defined in the high energy limit for massless quarks, we finally take quark masses to be zero.

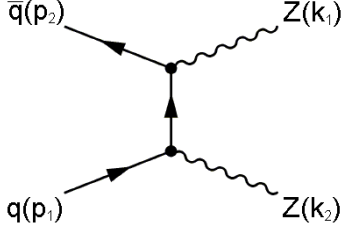


FIG. 1: Standard model contribution due to a t-channel quark exchange. The quark line  $q$  can represent any Standard Model quark.

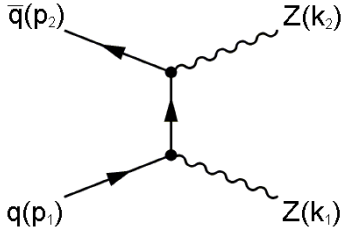


FIG. 2: Standard model contribution due to a t-channel quark exchange and crossed final momenta  $k_1$  and  $k_2$ . The quark line  $q$  can represent any Standard Model quark.

Concerning the contributions through graviton mediation all processes induced by a quark anti-quark pair can be neglected. The probability for the transition of a quark anti-quark pair to a ZZ-pair mediated by a single graviton  $S_{graviton}(q + \bar{q} \rightarrow ZZ)$  is exactly zero and all other processes leading to such a transition and involving a graviton are of higher order. Therefore, only the

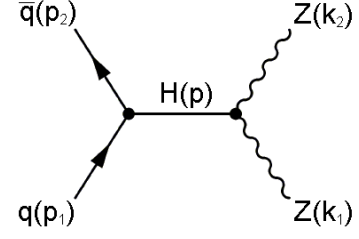


FIG. 3: Standard Model contribution due to Higgs boson in the s-channel. The quark line  $q$  can represent any Standard Model quark.

process where gluons annihilate and produce a graviton which couples to two Z-bosons remains at this order of perturbative expansion. This process has different external particles than the SM process where only the quarks give a contribution to the double Z-boson production rate. Thus, the contribution by graviton exchange can be regarded separately. At tree-level, the S-Matrix for the transition from a gluon pair to a ZZ-pair by mediation of a graviton corresponding to the Feynman graph (Figure (4)) is given by

$$\begin{aligned}
 S_{graviton} & (g(k_1, g_1) + g(k_2, g_2) \rightarrow Z(l_1, Z_1) + Z(l_2, Z_2)) \\
 &= \frac{1}{(2\pi)^4} \int d^4k \frac{g_{1\alpha a}}{(2\pi)^{\frac{3}{2}} \sqrt{k_{10}}} \frac{g_{2\beta b}}{(2\pi)^{\frac{3}{2}} \sqrt{k_{20}}} \\
 & \quad \left( -\frac{i}{\bar{M}_P} \delta^{ab} [W^{\mu\nu\alpha\beta} + W^{\nu\mu\alpha\beta}] \right) \\
 & \quad \cdot (2\pi)^4 \delta^4(k_1 + k_2 - k) \\
 & \quad \sum_n \frac{i P_{\mu\nu\rho\sigma}}{k^2 - m_n^2} (2\pi)^4 \delta^4(k - l_1 - l_2) \\
 & \quad \cdot \left( -\frac{i}{\bar{M}_P} [W^{\rho\sigma\gamma\delta} + W^{\sigma\rho\gamma\delta}] \right) \\
 & \quad \frac{Z_{1\gamma}}{(2\pi)^{\frac{3}{2}} \sqrt{l_{10}}} \frac{Z_{2\delta}}{(2\pi)^{\frac{3}{2}} \sqrt{l_{20}}} , \tag{12}
 \end{aligned}$$

where  $\bar{M}_P = M_P/\sqrt{8\pi}$  and  $W^{\mu\nu\alpha\beta}$  is defined as

$$\begin{aligned}
 W^{\mu\nu\alpha\beta} &= \frac{1}{2} \eta^{\mu\nu} (k_1^\beta k_2^\alpha - k_1 \cdot k_2 \eta^{\alpha\beta}) + \eta^{\alpha\beta} k_1^\mu k_2^\nu \\
 &+ \eta^{\mu\alpha} (k_1 \cdot k_2 \eta^{\nu\beta} - k_1^\beta k_2^\nu) - \eta^{\mu\beta} k_1^\nu k_2^\alpha . \tag{13}
 \end{aligned}$$

according to the expressions for the vertices found in [9]. Note that  $g_{1\alpha a}/2\beta b$  and  $Z_{1\gamma}/2\delta$  denote the polarization vectors of the gluons and Z-bosons respectively, where greek letters denote Lorentz-indices and latin letters as indices refer to the internal colour-space of QCD. Further  $k_1$  and  $k_2$  denote the initial momenta of the gluons and  $Z_1$  and  $Z_2$  denote the final momenta of the Z-bosons. The expression for the S-matrix (12) can be transformed to

$$\begin{aligned}
S_{\text{graviton}} &= \frac{-i}{(2\pi)^2 \sqrt{2k_{10}} \sqrt{2k_{20}} \sqrt{2l_{10}} \sqrt{2l_{20}}} \\
&\cdot \frac{1}{\bar{M}_P^2} \sum_n \frac{1}{p^2 - m_n^2} g_{1\alpha} g_{2\beta} [W^{\mu\nu\alpha\beta} + W^{\nu\mu\alpha\beta}] \\
&\cdot P_{\mu\nu\rho\sigma} [W^{\rho\sigma\gamma\delta} + W^{\sigma\rho\gamma\delta}] Z_{1\gamma} Z_{2\delta} \\
&\cdot \delta^4(p - l_1 - l_2) \quad , \quad (14)
\end{aligned}$$

where we have integrated over the first delta-function and  $p$  defined as  $p = k_1 + k_2$ . Using the symmetry of  $P_{\mu\nu\rho\sigma}$  in  $\mu, \nu$  and  $\rho, \sigma$  respectively, the expression (14) reads

$$\begin{aligned}
S_{\text{graviton}} &= \frac{-4i}{(2\pi)^2 \sqrt{2k_{10}} \sqrt{2k_{20}} \sqrt{2l_{10}} \sqrt{2l_{20}}} \frac{1}{\bar{M}_P^2} \sum_n \frac{1}{p^2 - m_n^2} \\
&g_{1\alpha} g_{2\beta} W^{\mu\nu\alpha\beta} P_{\mu\nu\rho\sigma} W^{\rho\sigma\gamma\delta} Z_{1\gamma} Z_{2\delta} \\
&\cdot \delta^4(p - l_1 - l_2) \\
&\equiv -i2\pi \delta^4(p - l_1 - l_2) \cdot \mathcal{M} \quad , \quad (15)
\end{aligned}$$

where  $\mathcal{M}$  denotes the Feynman amplitude. The polarization vectors are perpendicular to the corresponding momentum

$$k_{1\mu} g_1^\mu = 0 \quad , \quad k_{2\mu} g_2^\mu = 0 \quad , \quad l_{1\mu} Z_1^\mu = 0 \quad , \quad l_{2\mu} Z_2^\mu = 0. \quad (16)$$

Further the calculation shall be considered in the center of mass system meaning that the following relations are valid

$$\vec{k}_1 = -\vec{k}_2 \quad , \quad \vec{p} = 0 \quad , \quad \vec{l}_1 = -\vec{l}_2 \quad . \quad (17)$$

Thus, by using (11) and (13) one obtains for the Feynman amplitude

$$\begin{aligned}
\mathcal{M} &= 4A \cdot g_{1\alpha} g_{2\beta} \left[ -\frac{1}{2} \eta^{\mu\nu} (k_1 \cdot k_2) (g_1 \cdot g_2) \right. \\
&+ (g_1 \cdot g_2) (k_1^\mu k_2^\nu) + (k_1 \cdot k_2) g_1^\mu g_2^\nu \left. \right] \\
&\cdot \left[ \frac{1}{2} (\eta_{\mu\rho} \eta_{\nu\sigma} + \eta_{\mu\sigma} \eta_{\nu\rho}) - \frac{1}{3} \eta_{\mu\nu} \eta_{\rho\sigma} \right. \\
&- \frac{1}{2m^2} (\eta_{\mu\rho} p_\nu p_\sigma + \eta_{\nu\sigma} p_\mu p_\rho + \eta_{\mu\sigma} p_\nu p_\rho + \eta_{\nu\rho} p_\mu p_\sigma) \\
&+ \frac{1}{3m^2} \eta_{\rho\sigma} p_\mu p_\nu + \frac{1}{3m^2} \eta_{\mu\nu} p_\rho p_\sigma + \frac{2}{3m^4} p_\mu p_\nu p_\rho p_\sigma \left. \right] \\
&\cdot \left[ -\frac{1}{2} \eta^{\rho\sigma} (l_1 \cdot l_2) (Z_1 \cdot Z_2) + (Z_1 \cdot Z_2) (l_1^\rho l_2^\sigma) \right. \\
&+ (l_1 \cdot l_2) Z_1^\rho Z_2^\sigma \left. \right] \quad , \quad (18)
\end{aligned}$$

with  $A = \frac{1}{(2\pi)^3 \sqrt{2k_{10}} \sqrt{2k_{20}} \sqrt{2l_{10}} \sqrt{2l_{20}}} \sum_n \frac{1}{\bar{M}_P^2} \frac{1}{p^2 - m_n^2}$  and  $k_1 \cdot k_2 = k_{1\mu} k_2^\mu$ . Note, that the polarisation tensor of the graviton is on-shell meaning that  $p^2 = m^2$ . In gen-

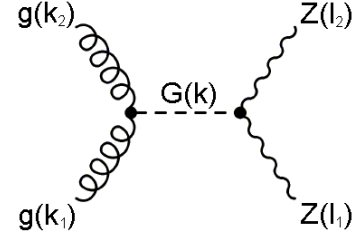


FIG. 4: ZZ-production due to the annihilation of two gluons into a virtual graviton

eral the differential cross section is related to the squared Feynman amplitude  $|\mathcal{M}|^2$  by the following expression

$$d\sigma = \frac{(2\pi)^4}{2} \sum_\sigma |\mathcal{M}|^2 E \sqrt{E^2 - m_Z^2} \sin(\theta) d\Omega \quad . \quad (19)$$

Thus, the expression (18) has to be squared. The summation over the polarization vectors of the Z-bosons and the gluons can be performed by using the relations

$$\sum_\sigma g_\mu g_\nu^* = -\eta_{\mu\nu} \quad , \quad \sum_\sigma Z_\mu Z_\nu^* = \left( -\eta_{\mu\nu} + \frac{l_\mu l_\nu}{m_Z^2} \right) \quad . \quad (20)$$

In order to obtain the total cross section one finally needs to integrate over the scattering angle  $\theta$ . The infinite sum over Kaluza-Klein excitations ( $\sum_n 1/(s - m_n^2)$ ) is treated with dimensional regularization [9]. By taking the lowest dimensional contribution ( $c_1 = 1$  and  $c_i = 0$  for  $i \neq 1$ ) and by choosing the regularization scale to be on the order of the new fundamental mass scale  $\Lambda = M_D$  one finds

$$\sum_n \frac{1}{s - m_n^2} \approx \frac{\bar{M}_P^2 \pi^{\frac{d}{2}}}{\Gamma(\frac{d}{2}) M_D^d} \quad . \quad (21)$$

Other approximations for the sum over the Kaluza Klein excitations are given in [11, 38, 39]. However, in our consideration we use equation (21).

This leads to the cross section

$$\sigma(gg \rightarrow ZZ) = \frac{\pi^d \sqrt{\frac{\hat{s}}{4}} \sqrt{\frac{\hat{s}}{4} - m_Z^2} Z}{\Gamma^2(\frac{d}{2}) M_D^8 30\pi m_Z^4} \quad (22)$$

with

$$\begin{aligned}
Z &= 13.875 \hat{s}^4 - 115.625 \hat{s}^3 m_Z^2 + 311.0625 \hat{s}^2 m_Z^4 \\
&- 314.250 \hat{s} m_Z^6 + 98 m_Z^8 \quad . \quad (23)
\end{aligned}$$

This is the inclusive cross section as a function of the number of extra dimensions  $d$  and the Planck mass  $M_D$  in  $4 + d$  dimensions.

#### IV. RESULTS

To obtain the cross section for the (anti-)proton-proton process one finally integrates over the parton distribution

functions denoted by  $f$

$$\begin{aligned} & \sigma(p(K_1)p(K_2) \rightarrow Z(l_1)Z(l_2)) \\ &= \sum_{i,j} \int_0^1 dx_2 \int_0^1 dx_1 f_i(x_1, Q) f_j(x_2, Q) \\ & \quad \sigma(\tilde{p}_i(k_1)\tilde{p}_j(k_2) \rightarrow Z(l_1)Z(l_2)) \quad , \quad (24) \end{aligned}$$

where  $\tilde{p}_i$  denotes the parton (whether this is a quark or a gluon depends on the index  $i$ ) that is contributing to the process,  $k_1 = x_1 K_1$ , and  $k_2 = x_2 K_2$ . The parton distribution functions (given in [40]) are evaluated at a scale of  $Q = \sqrt{s}$  for the process corresponding to figure (4) and at a scale of  $Q = m_Z$  for the processes corresponding to figure (1), figure (2) and figure (3).

In figure (5) the inclusive cross section at the Fermilab energy of 2000 GeV is depicted as a function of the fundamental Mass scale  $M_D$ , (starting from the lowest bound allowed by the unitarity constraint [9]). One sees that at  $M_D > 2500$  GeV graviton mediation according to the theory described above does not have any observable influence on the ZZ rate at Fermilab [41].

The same analysis is shown in figure (6) for pp reaction at an energy of 14000 GeV being available at LHC. Here, the drastic difference between the SM di-Z-boson rate and the graviton mediated di-Z-boson rate might allow to observe effects of large extra dimensions even for a fundamental scale of  $M_D \sim 18000$  GeV. Figure (6) shows that at  $\sqrt{s}=14000$  GeV, the ADD result dominates the SM prediction for small  $M_D \ll \sqrt{s}$ . This might reflect the fact, that the regularization method and the perturbative field theory approach loose validity in this regime. Therefore, it is more reasonable to take the results depicted in figures (5) and (6) only close to the regime of its validity  $\sqrt{s} \sim M_D$ . This allows to state from which  $M_D$  on experimental deviations from the SM ZZ rate at LHC [42] should be expected. In figure (7) the testable parameter space is depicted for the LHC and Tevatron experiments [45]. For experimental observation one would have to look for two high energetic and correlated lepton pairs in the final state as  $Z \rightarrow l^+ l^-$ . By multiplying the total cross section with the branching ratio  $\eta$  this cross section can be estimated. The branching ratio can be obtained by taking the ratio of the couplings in the leptonic channels to the couplings in all fermionic channels (the square appears because both Z-bosons should convert to a di-lepton pair).

$$\eta = \left( \frac{(\frac{1}{2} - \sin^2(\theta_W))^2 + \sin^4(\theta_W)}{2 - 4\sin^2(\theta_W) + \frac{16}{3}\sin^4(\theta_W)} \right)^2 \approx 0.01 \quad , \quad (25)$$

where  $\theta_W$  is the Weinberg angle at the Z-scale and  $\sin^2(\theta_W) \approx 0.23$ .

## V. SUMMARY AND DISCUSSION

Within the ADD model we have calculated the additional contribution to the double Z-boson production

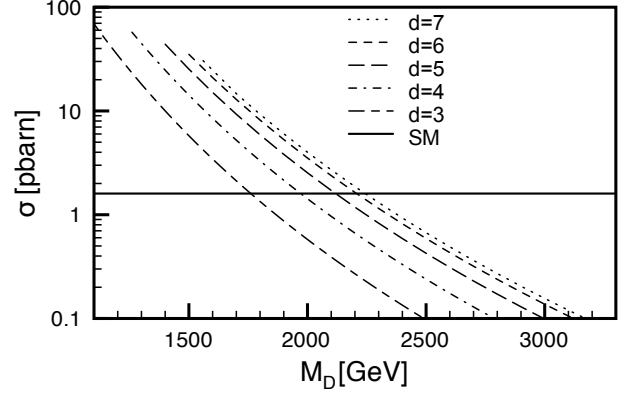


FIG. 5: Comparison between the inclusive  $p\bar{p} \rightarrow ZZ$  production cross section for the SM [43], the Fermilab [41] limit and the ADD model ( $d = 3, 4, 5, 6, 7$ ) for  $\sqrt{s} = 2000$  GeV in dependence of  $M_D$ .

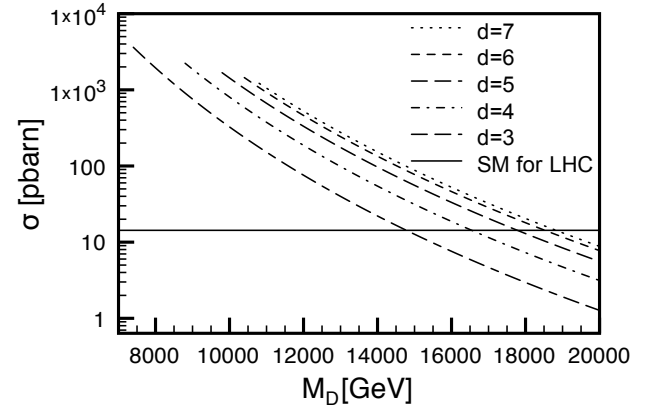


FIG. 6: Comparison between the inclusive  $pp \rightarrow ZZ$  production cross section for the SM [42] and the ADD model ( $d = 3, 4, 5, 6, 7$ ) for  $\sqrt{s} = 14000$  GeV in dependence of  $M_D$ .

cross section in  $pp, \bar{p}p$  reactions at high energies. The calculation is done to lowest order in  $\sqrt{\alpha_{ew,strong}}$  and the ratio  $m_X/M_D$ . It is found that the standard ZZ-production rate would be significantly enhanced compared to the SM rate, if the ADD scale would be lower than 15000 GeV in case of the LHC, respectively 1700 GeV in case of the Tevatron. For the case of seven extra dimensions even  $M_D = 18000$  GeV could be tested at LHC.

In consideration of such results we want to remind the reader that the magnitude of the ADD contribution (22) directly depends on the chosen regularization scale  $\Lambda$  in equation (21). But a choice of  $\Lambda = M_D$  is natural and because of the fact that we only took the lowest dimensional term of the regularized graviton sum (see [9]).

Therefore, if an enhancement above the SM ZZ-production rate would be observed at LHC energies, it can provide important insights into the possibly higher dimensional structure of space-time.

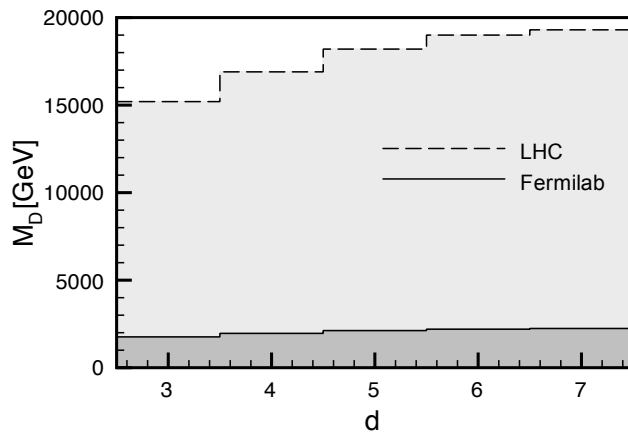


FIG. 7: ADD model parameter space accessible (i.e. when the additional cross section is at least as big as the SM cross section) in the ZZ-channel for the Tevatron and the LHC.

#### Acknowledgement:

We want to thank Elliot Lipeles for helpful comments . This work was supported by GSI, BMBF and FIAS.

- 
- [1] T. Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys. ) **1921**, (1921) 966.
  - [2] O. Klein, Z. Phys. **37** (1926) 895 [Surveys High Energ. Phys. **5** (1986) 241].
  - [3] I. Antoniadis, S. Dimopoulos and G. R. Dvali, Nucl. Phys. B **516** (1998) 70 [arXiv:hep-ph/9710204].
  - [4] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **436** (1998) 257 [arXiv:hep-ph/9804398].
  - [5] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429** (1998) 263 [arXiv:hep-ph/9803315].
  - [6] L. Randall and R. Sundrum, Phys. Rev. Lett. **83** (1999) 3370 [arXiv:hep-ph/9905221].
  - [7] L. Randall and R. Sundrum, Phys. Rev. Lett. **83** (1999) 4690 [arXiv:hep-th/9906064].
  - [8] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Rev. D **59** (1999) 086004 [arXiv:hep-ph/9807344].
  - [9] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **544** (1999) 3 [arXiv:hep-ph/9811291].
  - [10] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **595** (2001) 250 [arXiv:hep-ph/0002178].
  - [11] T. Han, J. D. Lykken and R. J. Zhang, Phys. Rev. D **59** (1999) 105006 [arXiv:hep-ph/9811350].
  - [12] C. Balazs, H. J. He, W. W. Repko, C. P. Yuan and D. A. Dicus, Phys. Rev. Lett. **83** (1999) 2112 [arXiv:hep-ph/9904220].
  - [13] J. L. Hewett, Phys. Rev. Lett. **82** (1999) 4765 [arXiv:hep-ph/9811356].
  - [14] J. L. Hewett and M. Spiropulu, Ann. Rev. Nucl. Part. Sci. **52** (2002) 397 [arXiv:hep-ph/0205106].
  - [15] E. A. Mirabelli, M. Perelstein and M. E. Peskin, Phys. Rev. Lett. **82** (1999) 2236 [arXiv:hep-ph/9811337].
  - [16] V. A. Rubakov, Phys. Usp. **44** (2001) 871 [Usp. Fiz. Nauk **171** (2001) 913] [arXiv:hep-ph/0104152].
  - [17] S. Cullen and M. Perelstein, Phys. Rev. Lett. **83** (1999) 268 [arXiv:hep-ph/9903422].
  - [18] S. Cullen, M. Perelstein and M. E. Peskin, Phys. Rev. D **62** (2000) 055012 [arXiv:hep-ph/0001166].
  - [19] T. Banks and W. Fischler, arXiv:hep-th/9906038.
  - [20] L. J. Hall and D. R. Smith, Phys. Rev. D **60** (1999) 085008 [arXiv:hep-ph/9904267].
  - [21] V. D. Barger, T. Han, C. Kao and R. J. Zhang, Phys. Lett. B **461** (1999) 34 [arXiv:hep-ph/9905474].
  - [22] T. G. Rizzo, Phys. Rev. D **59** (1999) 115010 [arXiv:hep-ph/9901209].
  - [23] R. Emparan, M. Masip and R. Rattazzi, Phys. Rev. D **65** (2002) 064023 [arXiv:hep-ph/0109287].
  - [24] K. Agashe and N. G. Deshpande, Phys. Lett. B **456** (1999) 60 [arXiv:hep-ph/9902263].
  - [25] S. B. Giddings and S. D. Thomas, Phys. Rev. D **65** (2002) 056010 [arXiv:hep-ph/0106219].
  - [26] S. Dimopoulos and G. L. Landsberg, Phys. Rev. Lett. **87** (2001) 161602 [arXiv:hep-ph/0106295].
  - [27] D. M. Eardley and S. B. Giddings, Phys. Rev. D **66**, 044011 (2002) [arXiv:gr-qc/0201034].
  - [28] M. Bleicher, S. Hofmann, S. Hossenfelder and H. Stoecker, Phys. Lett. B **548** (2002) 73 [arXiv:hep-ph/0112186].
  - [29] S. Hossenfelder, S. Hofmann, M. Bleicher and H. Stoecker, Phys. Rev. D **66** (2002) 101502 [arXiv:hep-ph/0109085].
  - [30] D. V. Galtsov, Phys. Rev. D **66** (2002) 025016 [arXiv:hep-th/0112110].
  - [31] V. Cardoso, O. J. C. Dias and J. P. S. Lemos, Phys. Rev. D **67** (2003) 064026 [arXiv:hep-th/0212168].
  - [32] B. Koch and M. Bleicher, arXiv:hep-th/0512353.
  - [33] J. Ruppert, C. Rahmede and M. Bleicher, Phys. Lett. B **608** (2005) 240 [arXiv:hep-ph/0501028].
  - [34] B. Koch, H. J. Drescher and M. Bleicher, Astropart. Phys. **25** (2006) 291 [arXiv:astro-ph/0602164].
  - [35] S. C. Park, H. S. Song and J. H. Song, Phys. Rev. D **65**, 075008 (2002) [arXiv:hep-ph/0103308].
  - [36] P. Callin and F. Ravndal, Phys. Rev. D **72** (2005) 064026 [arXiv:hep-ph/0412109].
  - [37] U. Baur, O. Brein, W. Hollik, C. Schappacher and D. Wackeroth, Phys. Rev. D **65** (2002) 033007 [arXiv:hep-ph/0108274].
  - [38] J. Hewett and T. Rizzo, arXiv:0707.3182 [hep-ph].

- [39] D. F. Litim and T. Plehn, arXiv:0707.3983 [hep-ph].
- [40] S. Kretzer, H.L. Lai, F. Olness, W.K. Tung Phys. Rev. D **69** (2004) 114005 [arXiv:hep-ph/0307022].
- [41] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **71** (2005) 091105 [arXiv:hep-ex/0501021].
- [42] J. Ohnemus, arXiv:hep-ph/9503389.
- [43] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60** (1999) 113006 [arXiv:hep-ph/9905386].
- [44] To be specific, it is not the lowering of the Planck scale, but the increase of the available phase space that increases the effective coupling to gravitons within the ADD model. At high enough energies, this is equivalent to a reduction of the Planck scale.
- [45] It should be mentioned that by taking the approximation for the summation over the Kaluza-Klein states given in [11], the  $d$  dependence of the results differs decisively from the  $d$  dependence obtained here